

PRESENT AND FUTURE NAVAL APPLICATIONS FOR PULSED POWER

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Abstract

Like many industrial organizations, the US Navy is moving away from an era of hydraulic, pneumatic and mechanical devices to an era dominated by electromechanical devices and all-electric controls. The Navy is also moving to replace many traditional weapon systems (all of which are chemical and thermodynamic in nature) with directed energy and electric weapons. For these applications there are few, if any, analogies to industrial applications. Some of the electromechanical devices, such as the electromagnetic aircraft launch system (EMALS) and all the electric weapons under development, such as the electromagnetic (EM) railgun and the high-energy laser, require some form of pulsed power and/or pulse forming network. The stored energy necessary to operate these devices may range from tens of kilojoules to several gigajoules, and their instantaneous power may exceed 20 gigawatts.

This paper will discuss the options available to provide these energy and power levels and will discuss the research and engineering challenges that need to be overcome for successful operation and fielding.

I. FUTURE NAVAL WEAPON SYSTEMS REQUIREMENTS

A. Railguns

In the last few years, the US Navy has taken an interest in the development of large electromagnetic (EM) railguns for long-range (in excess of 200 miles) operations. (See [1–4] for example.) To reach these ranges with a useful payload, gun sizes of about 150 mm bore diameter with lengths of 10–12 m will be necessary. Projectile launch masses are expected to exceed 20 kg with muzzle velocities of over 2000 m/s and corresponding muzzle energies > 60 MJ. This will require pulsed power systems capable of providing over 100 MJ of energy into the railgun breech per shot. For breech-fed single-rail systems, this energy pulse will be over 5 MA at a voltage up to about 20 kV. A typical pulse length will be a few milliseconds, corresponding to the transit time of

the projectile through the barrel. Ideal pulse shapes would minimize the peak-to-mean accelerating pressure (the piezometric ratio) and acceleration ripple while ensuring that the projectile leaves the muzzle without significant current interruption.

B. High-Energy Lasers

The proliferation of subsonic and supersonic anti-ship cruise missiles continues to present the US Navy with a significant challenge in ship self defense. The extremely small radar cross section and low-altitude flight capability of these missiles make them very difficult to detect in even the most favorable conditions. Consequently, the characteristics required of a self-defense system are quick reaction, rapid fly-out, and high lethality. High-energy lasers promise to deliver all these attributes. However, to deliver sufficient energy to the target to achieve a kill with a dwell time on the order of a few or several seconds will require power levels at the pointing aperture of perhaps 1–4 MW). Even with a 10% efficiency laser system, this combination of output power and dwell time could call for upward of several hundred megajoules of stored energy per engagement. As a final difficulty, it is yet uncertain whether these lasers would be of a solid-state, free-electron, or other design. Each of these approaches would require roughly the same level of stored energy, but voltage and phase characteristics would differ greatly.

C. Aircraft Launch

The Navy has already proceeded down the path of an electromagnetic aircraft launch system (EMALS) to replace the steam-powered catapults on future aircraft carriers and for possible retrofit on existing ships [5]. The current design, which is proceeding through a system development and demonstration phase, stores several hundred megajoules of energy in a rotating machine approach (see Figure 1). The rotating machine energy-storage technology was mature enough to support this near-term application and fit within the space and weight

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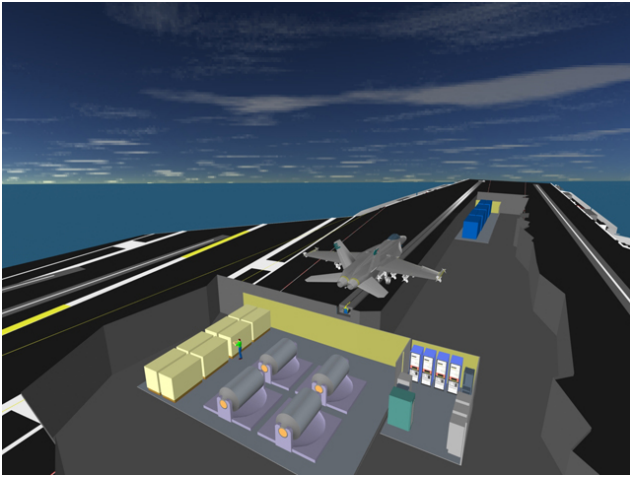


Figure 1. EMALS concept.

constraints of the aircraft carrier. However, space is not unlimited, even on an aircraft carrier. The Navy still desires to reduce the size and mass of the EMALS pulsed power system in the future, and this is likely to require additional technology maturation or a different approach.

D. Radars

Due to their ability to reposition over a significant portion of the Earth's surface, naval ships are seen as a valuable asset in detecting and countering ballistic missile threats. Most naval ship radars fielded to date have been designed either to deal with targets with radar cross sections of several square meters and range of a few hundred miles, or with a small fraction of a square meter's cross section and a few miles' range. These combinations have resulted in radars with average power output on the order of a megawatt and peak power output of a few megawatts. The performance requirements for the radars that will be necessary to support ballistic missile defense are much higher. This mission will require radars that can discriminate very small targets at distances in excess of a thousand miles. This will require radars with an average power output of several megawatts in search mode and perhaps in excess of 10 MW average power in the track mode. The electrical power quality required for these radars is very high and consequently very expensive. One possible alternative to designing a system to support the highest average power requirement of the radar would be to address the highest power and less-frequent tracking mode needs with a pulsed power system. This could significantly reduce the cost and size of the power system used for the continuous needs of the search mode.

E. Beamed Microwave

It was understood very early on in the development of short wavelength radar systems that, with sufficient energy, these radars could generate physical damage to electronic components. This realization has long since

been capitalized upon in the development and testing of many systems for a wide variety of applications. For short-range application against relatively "soft" targets, the power requirement for these systems is not terribly high. However, as these systems are only used in a pulsed mode and need to be as small as possible for ease of relocation and even portability, they have very high energy-density requirements. This combination of capabilities and operational constraints may open the door to the use of rather novel, and possibly even disposable or single-use, pulsed power systems.

II. ENERGY STORAGE AND PULSED POWER OPTIONS

The next generation of advanced surface combatant ship is expected to have over 100,000 hp of electrical power capability on board for ship propulsion. When not at full speed, a significant fraction of this power can be made available for recharging the pulsed power supplies required to provide the railgun breech energy to support high firing rates. Recharge power rates will be determined by the weapon systems requirements identified in the previous section—the needs of each individual load and the firing rates. Several approaches have been considered using different physical principles for energy storage: capacitors (electrostatic); pulsed alternators (inertial); inductors (magnetic); and batteries (chemical). These options are described briefly below.

A. Capacitors

Capacitors store energy electrostatically through the polarization of a dielectric material. A high-energy storage capacitor traditionally consists of an assembly of many rolls of dielectric material in a series-parallel arrangement that is matched to the need. Each roll consists of a large area of dielectric that has metallic anode and cathode material, typically metallized aluminum, on each side. The capacitor is charged from a high-voltage DC source and retains the charge, with some decay, until needed. The energy stored by the dielectric is determined by its permittivity (ϵ_r) and its operating voltage (V_{op}) which should be as close to the breakdown voltage of the film as is safe, according to the relationship

$$E = \frac{\epsilon_0 \epsilon_r E_{op}^2}{2}. \quad (1)$$

Typical capacitors are made in moderate-sized units, seldom storing more than about 100 kJ each, primarily for ease of handling during production. Most large systems therefore require assemblages of multiple units, integrated with protective fuses, crowbar switches and load switches. Figure 2 shows modules used in the Thunderbolt experiments of the late 1980s [6].



Figure 2. Thunderbolt experiment.

These units used paper dielectric with aluminum foil electrodes and stored ~ 0.3 kJ/kg. Newer capacitors use better films, such as polypropylene, and can store > 2 kJ/kg. Even higher values have been obtained with non-linear hysteretic films, such as PVDF and promising new materials are under development [7–9]. Nevertheless, it is likely that a large capacitor bank will be required for the largest energy storage and power deliver applications discussed in Section I. The extent to which this can be incorporated into the ship structure has yet to be assessed.

One issue that has to be addressed when estimating capacitor size and weight for the applications discussed here is thermal management. Capacitor dielectric materials are good electrical insulators and hence, with little exception, good thermal insulators. Therefore, although single-shot or short-burst operation can be accomplished, long-burst or continuous operation may demand a thermal management system that can be put in close proximity to the interior of the capacitors. This introduces weight and volume penalties, as well as a concern about electrical integrity. Relatively little has yet been done to address this issue.

B. Rotating Machines

High-speed rotors have the capability to store energy inertially that can then be extracted electrically. Various rotor topologies have been studied, but the one most commonly used is the drum configuration, similar to that used for utility generators. In operation, the rotor of such a machine will be spun up to speed by an externally driven electric or hydraulic motor or turbine over a period determined by the power rating of the motor and the supply system. The energy stored E is given by

$$E = \frac{I_m \omega^2}{2} \quad (2)$$

where I_m is the moment of inertia of the rotating portion of the machine and ω is the rotational speed, and the power delivery capability P is given (for an air-core machine) by

$$P = \frac{B_s^2 A_A V}{2\mu_0} \quad (3)$$

where B_s is the magnetic field strength at the stator winding, A_A is the active surface area of the rotor, V is the relative velocity of the magnetic field and the stator winding, and μ_0 is the permeability of free space.

Generally, it is found that the power delivery capability dominates the design process, so that when a configuration has been selected that will provide the required power rating, it will store more than the energy required for the given task. Discharging the energy stored inertially in the pulsed alternators into the load slows down the machine rotor, so prior to the next shot, the energy used has to be re-stored by spinning the machine rotors back up to their initial speed. In some cases where multi-pulse operation is required in rapid succession, additional inertia may need to be added to the rotor by adding mass.

Early railgun experiments used homopolar generators (HPGs) to provide high-current DC pulses but, since these are low-voltage machines, additional pulse compression circuitry was needed that made the operation more complex (e.g., [10, 11]). More recently, attention has turned to self-excited, air-cored pulsed alternators that generate high-voltage AC outputs, and over the last decade the US Army has invested in the development of lightweight, high-speed pulsed alternators for tactical vehicles (see Figure 3) [12]. The technology required for a large ship, and the commensurate risk, is much lower than needed for a lightweight tactical battlefield vehicle, so there is good confidence that a pulsed alternator could be designed for Navy applications with moderate risk. Multiple machines, arranged in contra-rotating pairs to mitigate torque reaction forces, provide the operational flexibility to supply different energy levels for different mission requirements. This arrangement provides a robust arrangement in terms of battle damage.

A disadvantage of the use of pulsed alternators (PAs) for some applications, such as the railgun, is that the PA produces AC power while the railgun uses DC power. With present silicon thyristor technology, this necessitates an output rectifier system that is a significant fraction of the size of the machine. A rectifier is also needed to self-excite the field coil. Development of improved switching

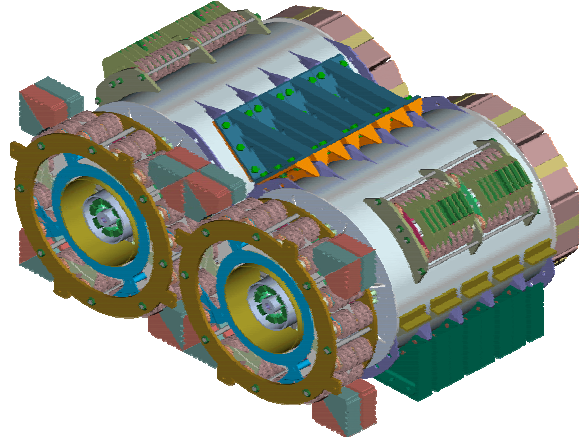


Figure 3. Pulsed alternator pair concept.

technology could reduce the size and complexity of these rectifiers, and silicon carbide and optical switching are promising approaches [13].

C. Batteries

Batteries are very effective at storing energy and are widely used in the Navy and for other applications. The most widely used large units rely on lead-acid technology. However, in recent years, substantial improvements have been made in lithium-ion technology, although at much higher costs [14]. Despite specific specialized “high-power” designs, batteries are not usually capable of delivering power at the rate required for a large railgun. Several of the early laboratory railgun systems (see, for example, Figure 4) were successfully operated using an intermediate inductive energy storage system in which an inductor was charged over a period of a few tenths of a second from an HPG, which was subsequently discharged into the railgun at the required power levels. Replacing the HPG with batteries would allow the inductor to be charged at a MW rate for a few seconds and then discharged at the GW rate for a millisecond period.

The energy stored magnetically E in such an inductor is given by

$$E = \frac{B^2}{2\mu_r\mu_0} \cdot \quad (4)$$

where B is the magnetic field strength and μ_r and μ_0 are the relative and absolute permeabilities, respectively. For a high-field, air-cored inductor, the relative permeability is unity.

With battery development, such an arrangement may eventually be smaller, and operate at a lower voltage, than a capacitor-based system. An important potential benefit compared with pulsed alternators is that there is no rotating machinery or auxiliaries of the type that are required there—seals, bearings, lubrication systems, vacuum systems, etc. However, a special switch is needed to transfer current from the inductor to the railgun; such switches are not readily available. A paper in this conference discusses a possible novel approach for this system [15]. Further evaluations of this arrangement should also include an assessment of the benefits of reducing inductor conductor temperatures to liquid nitrogen or even liquid helium temperatures to substantially reduce the resistive losses. The Office of Naval Research (ONR) has parallel programs to develop superconducting machines for ship propulsion, so additional on-board cryogenic components may not be charged with the full overhead of a cryogenic system. Figure 5 shows a 10 MJ liquid-nitrogen-cooled inductor that was built by Westinghouse Electromechanical Division (now Curtiss-Wright) and used in a railgun system for USAF Eglin and Westinghouse Sunnyvale (now Northrop-Grumman) in the late 1980s [16].

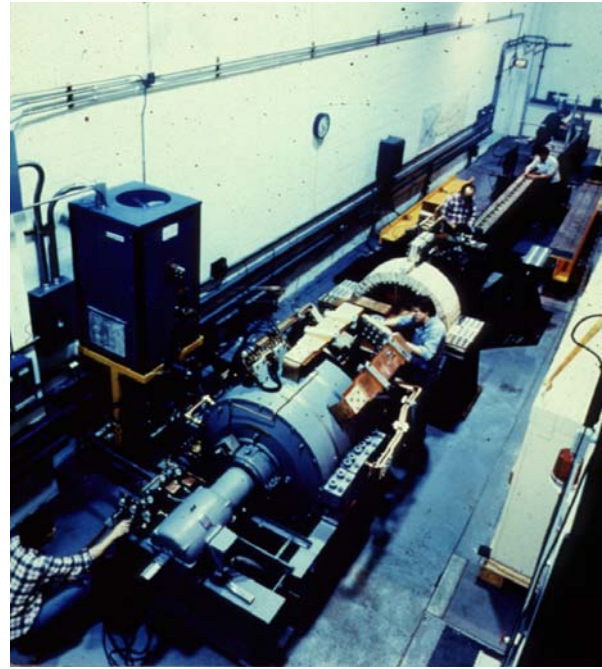


Figure 4. HPG-powered pulsed inductor for the Army EMACK EM Railgun.

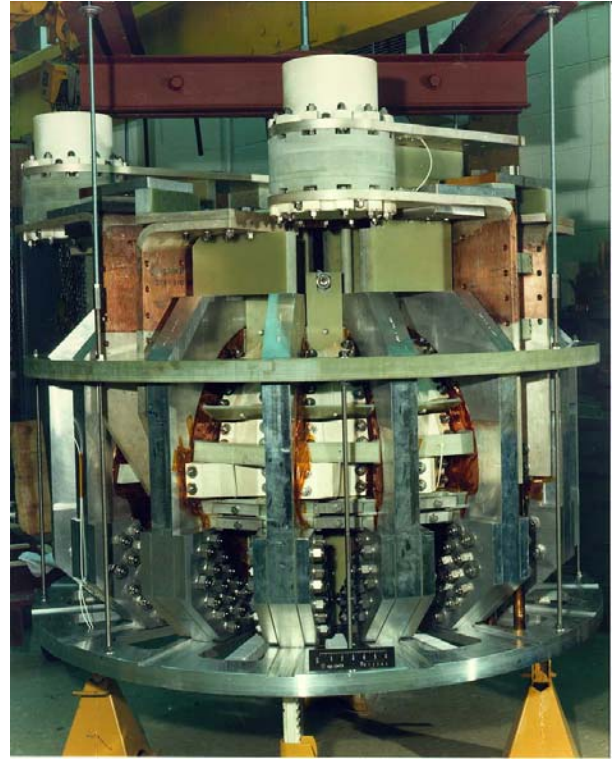


Figure 5. 10 MJ liquid nitrogen-cooled inductor before installation in cryogenic tank. (Courtesy Curtiss-Wright).

D. Superconducting Magnetic Energy Storage (SMES)

Evaluations of magnetic energy storage should also include an assessment of the benefits of using superconducting magnetic energy storage (SMES) technology. SMES systems have been developed primarily for utility applications where they can store sufficient energy to provide a short-term buffer in the event of a transient interruption of the utility supply in situations where assured power is needed, such as hospitals or critical manufacturing processes. The military also has critical situations where such systems could be used, for example, for flight operations or fire control radars. However, SMES technology is not yet widespread in the utility support industry and more work needs to be accomplished before it can be considered as a strong candidate for the naval applications. In addition, for the utility applications that are the main application focus, high voltage-low current characteristics are the norm, and this may not be the best match to all Navy applications.

E. Magnetic Flux Compression Generators

Many papers in this series of Pulsed Power as well as the Megagauss conferences have provided details on magnetic flux compression generators (MFCGs). These generators use high explosives to drive conductors that are carrying a “seed” current into close proximity or contact with a stator conductor. The rapid change in the physical size of the current loop causes very high magnetic fields and currents to be generated on a time scale that is consistent with the burning time of the explosive—usually tens of microseconds. MFCGs have been made in sizes ranging from the very large—generating currents of more than 100 MA—to units that can be contained within an artillery round to drive RF devices. Since the detonation of the explosive brings about the rapid disassembly of the structure, such devices are single-shot by nature. While they may have limited use in special cases, they are unlikely to have widespread impact to serve the loads identified in Section I.

F. Magnetohydrodynamic Generators

In a magnetohydrodynamic (MHD) generator, the flow of an electrically conducting gas (plasma) through a magnetic field generates a voltage that, when extracted through electrodes in a generator channel, can transfer current to an external load. The plasma can be produced by reacting fuel and oxidant, together with seeding by a material with low ionization potential, such as a potassium or cesium compound. Although considerable research was undertaken in the 1960s and 1970s on MHD for long-duration, low-current utility power generation, relatively little work has been done for short-pulse applications. Repetitive low-current (kA) pulses with a frequency of ~ 2 Hz and rise/fall times of tens of milliseconds were generated for a few seconds during operation of a liquid oxidizer/solid fuel rocket-driven generator in the US [17]. A Russian PAMIR generator was also procured and tested [18]. Explosively driven,

highly ionized argon systems have produced extremely high powers ($> \text{GW}$) and high currents ($> \text{MA}$) for tens of microseconds [19, 20].

The relatively low conductivity of most partially ionized plasmas limits the current that can be obtained from MHD generators to tens of kilo-amperes, rather than mega-amperes as required for large electric launchers. Thus, for most railguns, the currents normally produced by MHD generators would need to be transformed up via a pulse transformer. One Russian experiment to power a low-current railgun with an MHD generator via energy storage in an inductive current transformer has been reported [21].

III. MILITARY CONSIDERATIONS

Many of the advanced technology systems identified in Section I are in laboratory development at present. Most of these use capacitor power supplies for convenience, either because they are widely available or because they can easily be used and conveniently reconfigured in modular units to provide pulses with a wide range of characteristics in both power and frequency. When scientists and engineers analyze possible pulsed power options for the applications in Section I, they tend to focus on those options that can most efficiently power the application. While this is logical in a purist engineering approach, it is only one of three critical measures from the perspective of the weapon system engineer. At least equally important are how well the pulsed power system drives the weapon in the expected tactical employment and the engineering implications of integrating the system into the ship.

A. Tactical Employment

The concept of operations (CONOPS) for the weapon system is a very stressing and often overriding requirement in determining the pulsed power approach. Using the railgun as an example, a capacitor-based, pulse-forming network is an ideal candidate in the laboratory, as it can be tailored to provide the optimum pulse shape for a given railgun design. However, if the weaponized railgun is to be used in a shore bombardment role that requires firing several hundred times per hour for perhaps several hours or even days, a capacitor approach may become intractable due to the heat that will build up within the capacitors because of their inherent internal resistance. This tactical employment may drive the engineer toward a less efficient solution but one that can more easily incorporate cooling into the energy storage module. Conversely, if the railgun is to be used in a ship self-defense role, it may need to be able to fire dozens of shots in only a few seconds to successfully defeat a threat to the ship. In this case, it may be necessary for the pulsed power system to store enough energy to fire all the shots required during the engagement without any regeneration

from the ship's primary power. This requirement may then favor a system that can deliver the highest energy density even if it means lower efficiency or even durability. As an example, a deck-mounted ship self-defense gun may need to have pulsed power systems that are closely connected and probably mounted in the same gun housing, as illustrated conceptually in Figure 6 [22].

B. Ship Integration

For all practical purposes a naval combatant is a highly mobile, floating, power plant. Typical combatants have in excess of 80 MW of installed power which with the implementation of all-electric ships will be able to be brought to bear for propulsion, sensors, and weapons in varying degrees as the tactical situation merits. A few of the prime concerns for ship integration of a pulsed power system are its physical size, weight, location within the ship, and auxiliaries' requirements. Again, using the railgun as an example, looking at a few ship integration issues is very illustrative.

Weight is usually viewed as a quantity that must be reduced to the greatest extent possible in weapon systems. In ships however, the merit of weight is relative in relationship to where it is with respect to the ship's center of gravity and center of buoyancy. Weight low in the ship, below the center of gravity, often has little impact as it can be offset with the removal of ballast. Consequently a pulsed power system that performs favorably but has a high weight factor in comparison to other alternatives may not be at a disadvantage if it can be placed low in the ship. Doing so will not only offset the relatively high (vertical) weight of the gun mount but also improve the ships sea-keeping performance. For example, it is likely that a large railgun of the type needed for long range shore bombardment will be a substantial and integral part of the ship in which it is mounted. Indeed, such an arrangement is shown conceptually in Figure 7.

In contrast, a deck-mounted ship self-defense gun will need to have pulsed power systems that are closely connected and probably mounted in the same gun housing, as shown in Figure 6.

Efficiency is often a key measure of the utility of a system. For a notional shipboard long-range bombardment railgun system, approximately three gallons of fuel will be necessary to generate the total electrical energy necessary for one shot, and approximately two thirds of that energy will be rejected as heat. Given this, one would expect that a pulsed power system that operates at half the efficiency of other alternatives would be dismissed out of hand. Quite the contrary is true. A surface combatant carries greater than half a million gallons of fuel and can be easily refueled at sea. Also, Navy ships operate in the world's largest liquid heat sink. Therefore, if the less-efficient pulsed power system performs well in other aspects of performance, such as reliability and energy density, even a 100% penalty in efficiency may have little impact in its overall utility from a ship integration perspective.

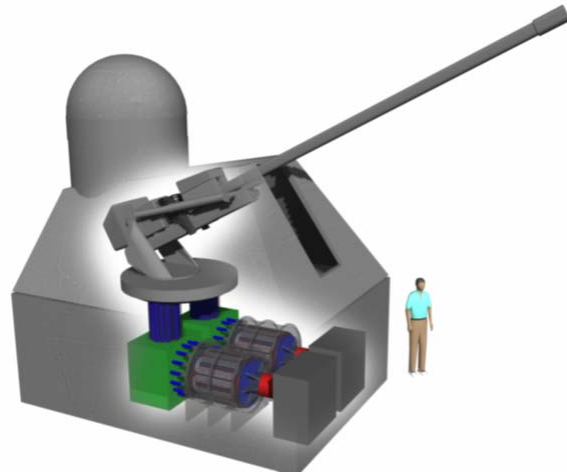


Figure 6. Ship self-defense concept.

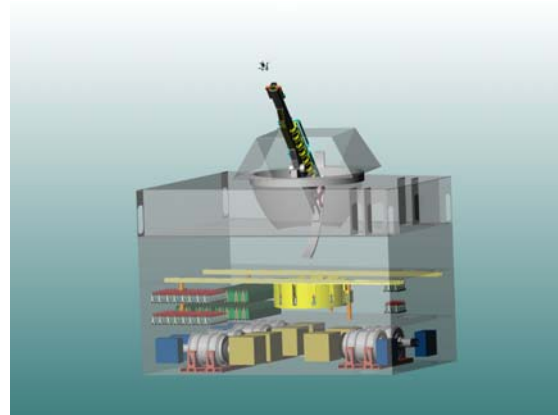


Figure 7. Ship layout for a long range railgun powered by three pairs of pulsed alternators. (Courtesy NSWC)

IV. SUMMARY AND FUTURE DIRECTIONS

The main conclusion from this brief overview is that, while fundamental studies on each of the "load" systems discussed above should continue (e.g., rail life for railguns, etc.), there needs to be more emphasis placed on an integrated view of the pulsed power system that incorporates the three aspects of weapon needs, mission needs, and operational and platform needs. In all these cases, an assessment will have to be made of the minimally acceptable, preferred optimal, and realistically practical levels of operation. The integrated higher-level view has to bring all these together to achieve at least a minimal acceptable solution for all relevant aspects. To achieve this requires experts from all these disciplines to sit down together and cooperate.

In addition, of course, as the community seeks to integrate multiple pulsed power technologies onto a single platform, the often-conflicting requirements of different pulsed power users need to be optimized to yield a practical and useful solution that will fulfill the Navy's future needs.

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